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Author(s): Natan, Tali Marshall

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SULI Research Report

Tali Natan, Mentored By Dr. Jeph Wang

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Abstract

Acoustic levitation allows for the containerless manipulation of small samples limited by density, size, and shape. Modern acoustic levitators are either constructed with Langevin horns, which need to be machined to high tolerance and require at least 100V, or ultrasonic transducers, which are robust to changes in temperature and require low voltage. We investigated the ability of the TinyLev, a commercially available single axis levitator, and prototyped a two-axis levitator. Both the TinyLev and our two-axis levitator employ phased arrays of transducers and operate at 40 kHz. Models produced with the Python toolbox Levitate showed the characteristic nodes of the TinyLev and found two previously unpublished "traps" (stable local pressure minima) of the two-axis levitator. We plan to use these levitators at the Advanced Photon Source (APS) to study a variety of samples, via white beam diffraction and high speed imaging. It is our goal to calculate the radial distribution function with respect to temperature across phase transitions.

1 Introduction

The rigorous study of acoustic levitation began in 1934 with King's study of incompressible particles in acoustic fields [1]. In 1955, Yosioka and Kawasima calculated the forces on compressible particles in plane acoustic waves [2]. Then in 1962, Gor'kov derived the radiation force produced by acoustic waves [3]. The following equations are for the radiation force on spherical particles (much smaller than the driving wavelength, $a \ll \lambda$) due to an acoustic potential in an inviscid fluid as derived by [4]

$$\boldsymbol{F^{rad}} = -\boldsymbol{\nabla} U^{rad} \tag{1}$$

$$U^{rad} = \frac{4\pi}{3} a^3 \left[f_1 \frac{1}{2\rho_M c_M^2} \langle p^2 \rangle - f_2 \frac{3}{4} \rho_M \langle v^2 \rangle \right] \tag{2}$$

$$f_1 = 1 - \frac{k_p}{k_M} \tag{3}$$

$$f_2 = \frac{2(\rho_p - \rho_M)}{(2\rho_p + \rho_M)} \tag{4}$$

$$U^{rad} = 2\pi a^3 \left[\frac{\langle p^2 \rangle}{3\rho_0 c_0^2} - \frac{\rho \langle v^2 \rangle}{2} \right] \tag{5}$$

$$U^{rad} = 2\pi a^3 \left[\frac{\langle p^2 \rangle}{3\rho_0 c_0^2} \right] \tag{6}$$

Here, a is the radius of the particle, ρ is the density, c is the sound speed, p is the pressure, v is the velocity, and k is the compressibility. In equations (1) - (4), subscripts M and p stand for "medium" and "particle" respectively. (5) is the common simplification for acoustic levitation in air where the subscript 0 refers to characteristics of air. One paper [5] neglects the entire velocity potential term yielding (6), thus the determining variables of a spherical sample's ability to be levitated is radius and density.

Acoustic levitation of materials allows for samples to be studied in a containerless environment. Unlike other forms of levitation such as electrostatic levitation and magnetic levitation, acoustic levitation is not constrained by a sample's charge or magnetism. One downside of acoustic levitation is that this method cannot be preformed in a vacuum thus the fluid in which a sample is analyzed must also be considered.

Langevin horns and phased arrays are the two main classes of acoustic levitators. Langevin horns, also known as acoustic horns, consist of machined pieces of metal made to match and amplify the frequency of an attached vibrating source. These sources may be ultrasonic transducers or piezoelectric disks and each horn must be precisely machined to its source's frequency. Langevin horns are driven with a high voltage, usually between 100V and 1000V, which makes the horns heats up; this changes their resonance so one needs to allow for a "warm up" time [6].

The phased array method came into vogue in 2015 with a paper entitled "Holographic acoustic elements for manipulation of levitated objects" by Asier Marzo and collaborators [6]. In this paper, the authors put forward a method of acoustic levitation consisting of a phased array of ultrasonic transducers. In a later paper, Marzo et al. presented the TinyLev, a single-axis acoustic levitator made up of two phased arrays of transducers [7]. This design is constructed from commercially available parts and a 3D printed frame. Marzo's team at UpnaLab published an accompanying Instructables article that shows one how to build the TinyLev https://www.instructables.com/Acoustic-Levitator/.

Before 2015, acoustic levitation, typically in the form of Langevin horns, was only available to a handful of facilities due to the precision machining and high voltage required. With the innovation of phased array acoustic levitators, the method has become much more accessible which has lead to an increase in interest and a growing number of applications. Acoustic levitation is being used to study fluid dynamics [8], containerless crystal growth [9], phase transitions [10], and researchers have been performing spectroscopic studies of suspended specimens [11]. Acoustic levitation also has applications in chemistry, biology, and pharmacology because of the techniques ability to control small samples without contamination [12] [13] [14].

2 TinyLev

The TinyLev is a single-axis non-resonant acoustic levitator made up of two spherical cap-shaped arrays of transducers [7]. Each array contains 36 40kHz transducers circularly packed and angled such that their normals point towards the focus. An Arduino Nano generates the square wave signals which is amplified by a L297N Dual H-Bridge motor driver. One advantage of the TinyLev is that the parts, besides the frame, are readily available and the wiring is not complex (Fig. 1). The frame must be 3D printed with a recommended nozzle size of 0.4mm. The TinyLev is able to levitate samples up to 3.98g cm^{-3} when operating at 30V_{pp} despite the transducers in the original paper being rated to 20V_{pp} maximum [7]. A later paper found that by upgrading the transducers and adjusting the distance between arrays to maximize amplitude pressure, mercury samples (13.6g cm^{-3}) could be levitated at 45V_{pp} with transducers rated $\leq 40V_{rms}$ [15].

2.1 Verification

The Levitate toolbox was developed by Carl Andersson to provide a collection of algorithms and design patterns to aid researchers working with acoustic levitation [16]. From this toolbox, we were able to model various set ups (single transducers, flat arrays, curved arrays, etc.) and output the sound pressure field in dB given a reference pressure of 20μPa.

The models in Fig. 2 do not predict the same number of central nodes; since the measurements used to make the model in Levitate were directly measured from my TinyLev and not the ideal TinyLev. This discrepancy could also be due to each model using a different value for the speed of sound in air. Regardless, the general shapes found in each pressure field are similar: there are regions of high pressure separated by smaller regions of low pressure with symmetry about the vertical axis between arrays.

In Fig. 3, we see the TinyLev levitating pieces of packing foam, a glass bead, soap bubbles, and water droplets. All of these samples were levitated at $\leq$ 15V. Our TinyLev produced more nodes than either of the models in Fig. 2 predicted. This is due to the altitude of our experiment; the models assumed normal temperature and pressure but Los Alamos National Laboratory is located 2,250m above sea level. The number of nodes produced is determined by the wavelength; the more wavelengths that "fit" between the fixed arrays, the more available nodes. Since the wavelength is equal to the sound speed divided by the frequency, a smaller sound speed caused by elevation (331m s^{-1} compared to 340m s^{-1} at sea level), would results in a smaller wavelength (8.275mm compared to 8.5mm [17]) therefore more nodes.

3 Two-Axis Acoustic Levitator

The two-axis acoustic levitator consists of two TinyLev frames set perpendicularly to one another. A 3D printed connector joins the two frames such that there is no offset between acoustic planes generated by each axis. The wiring of the two-axis acoustic levitator is slightly more complex than the wiring of the TinyLev but the components are the same (Fig. 4). I designed this such that the Arduino Nano could still use the code provided by Marzo et al. for the TinyLev. When switching between the 1D axis trap and phase trap, only the wires between the drivers and arrays need to be adjusted. Unlike the TinyLev, which has periodic nodes in the pressure field between arrays, the fields generated by the two-axis acoustic levitator have definitive central "traps" — stable local pressure minima — as well as periodic nodes. These can best be seen in the models produced with the python toolbox Levitate.

3.1 Verification

We modeled three traps which I have named the 1D axis trap, phase trap, and 2D axis trap. The 1D axis trap was first implemented in [5] with the latter two being our additions to the set of known acoustic levitation traps. For a 1D axis trap, one axis of the levitator must be shifted off the common origin by $\frac{\lambda}{2}$ along the plane. When all arrays are in phase with one another, a stable trap will be created where the axis intersect. This process can be replicated by moving one axis $\frac{n\lambda}{2}$ from the common origin but as n approaches half the maximum number of viable nodes in the system, the trap will become weaker, less symmetric, and the overall levitator will become more resonant. This method was first employed with Langevin Horns by [5]. When the axes of the levitator share a common origin, the Phase Trap is achieved by having arrays along the same axis in phase but arrays in the perpendicular axis out of phase. This results in a low pressure region surrounded three dimensionally by high pressure at the geometric center of the system. The 2D Axis Trap combines aspects from both previous methods; each axis should be shifted off from the common origin by $\frac{\lambda}{2}$ along the plane. When the arrays along the same axis are in phase but arrays in the perpendicular axis out of phase, a stable trap will be formed where the axes intersect (Fig. 5).

We compared our model of the 1D axis trap to [5] which employed 4 Langevin Horns emitting at 22.7 kHz to our set up which uses a total of 144 ultrasonic transducers across 4 arrays emitting at 40 kHz. Despite these differences, the models share many similarities. With respect to the difference of emitting wavelength, the central traps are at the same location surrounded by drastic pressure gradients (Fig. 6). While [5] estimates that the trap is along a saddle shaped pressure potential, our model indicates this region is more indicative of a well. Outside this central trap, there is a region of periodic nodes along each axis and in between these regions on the diagonal, there are "dead zones" of low pressure.

The resulting pressure field from the phase trap and axis trap do not appear to be very different from one another (Fig. 7). Again, there is a strong trap at the location indicated by Fig. 5 and periodic nodes along the axis. The pressure field of the phase trap is symmetric about the trap but the field produced by the 2D axis trap dead zones of differing strengths along each diagonal.

Various samples have been levitated using the 1D axis trap and phase trap including pieces of EPE packing foam, water droplets, and a glass bead (2.5g cm^{-3} [18]). Some of these demonstrations can be seen in Fig. 8. All of these samples were levitated at $\leq$ 15.2V.

4 Upcoming Experiments

I am currently working on an instrumental paper for the two-axis phased array levitator. In the paper, I will detail the design and prototype of this levitator and compare its ability to the TinyLev. Special attention will be paid to the maximum density and stability of levitated samples as well as the power required to levitate similar samples between the two acoustic levitators.

In the future, we plan to bring these levitators to the Advanced Photon Source (APS) at Argonne Natiomal Laboratory to study a variety of samples, via white beam diffraction and high speed imaging. One of my goals is to calculate and experimentally validate the radial distribution function with respect to temperature across the ice/water phase transition.

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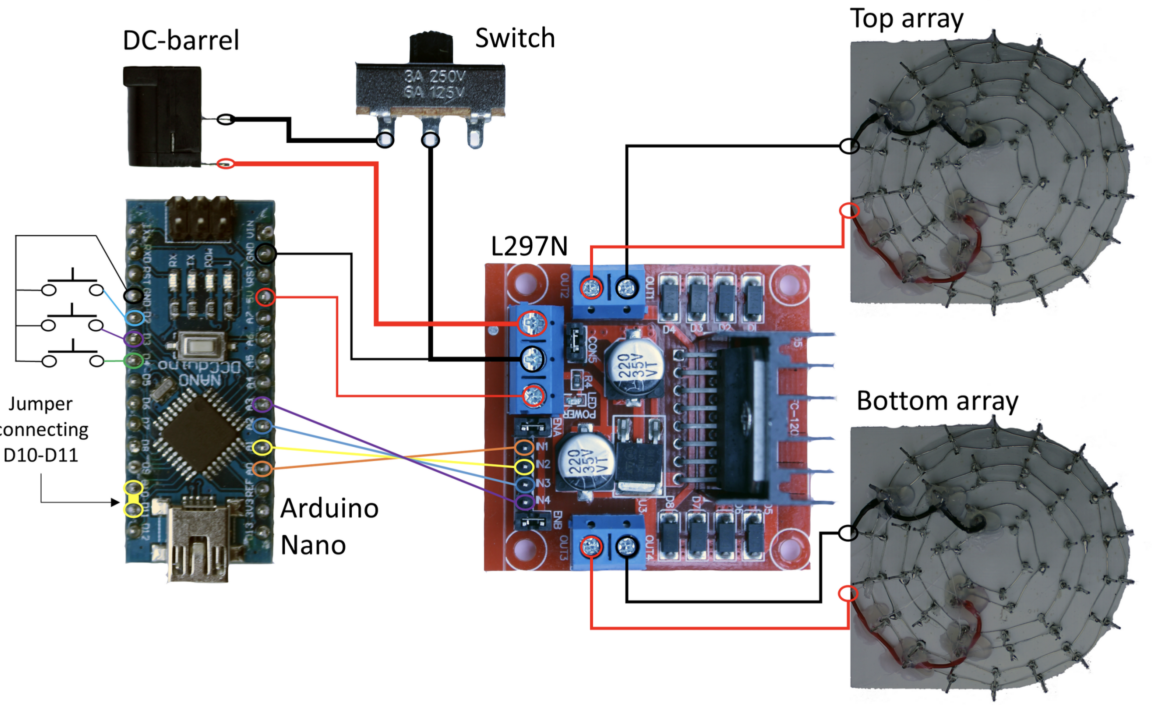

Figure 1: Wiring diagram for TinyLev published by UpnaLab in an Instructables article (https://www.instructables.com/Acoustic-Levitator/).

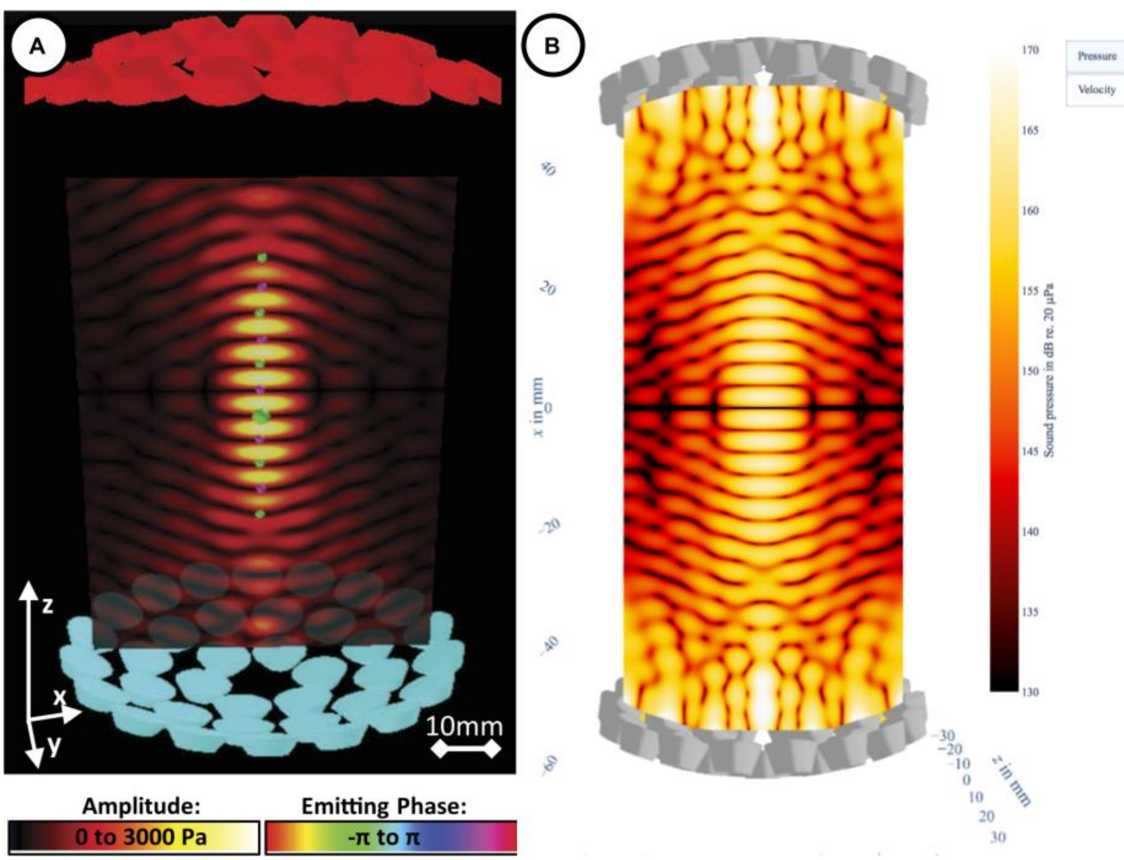

Figure 2: Models Comparison of TinyLev (A) is adapted from [7] (B) is generated from the Levitate toolbox.

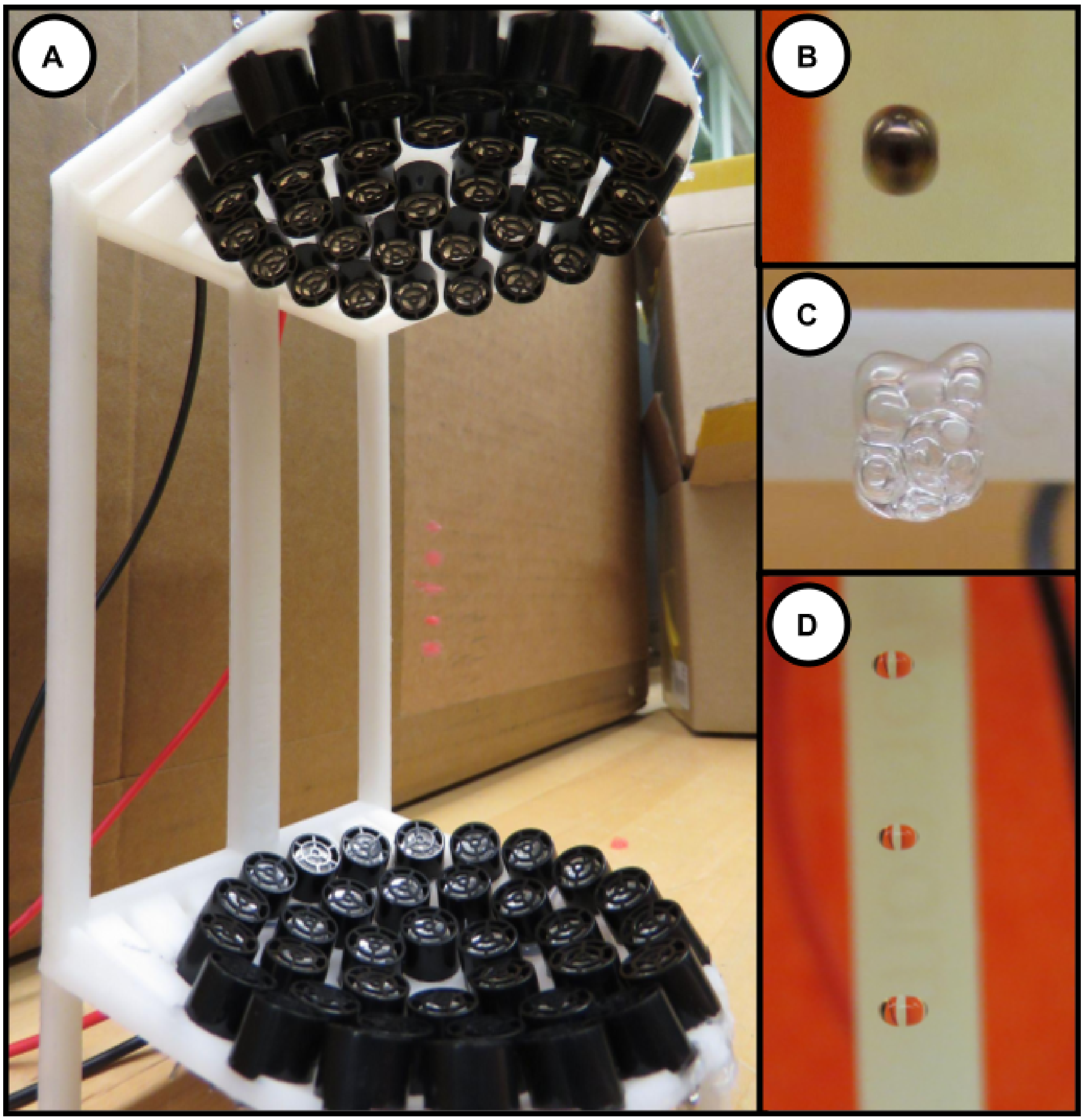

Figure 3: Various samples levitated by the TinyLev: (A) pieces of EPE packing foam (B) glass seed bead (C) soap bubble and (D) water droplets.

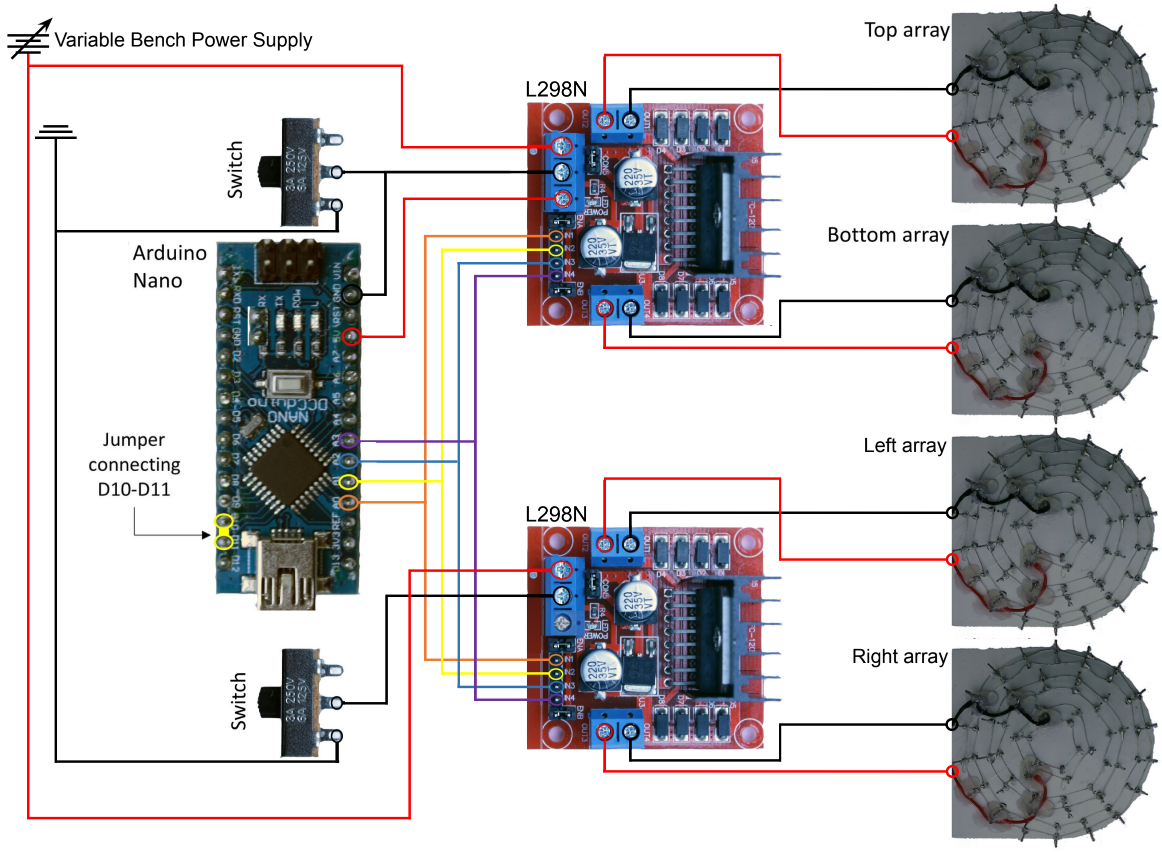

Figure 4: Wiring diagram for two-axis acoustic levitator.

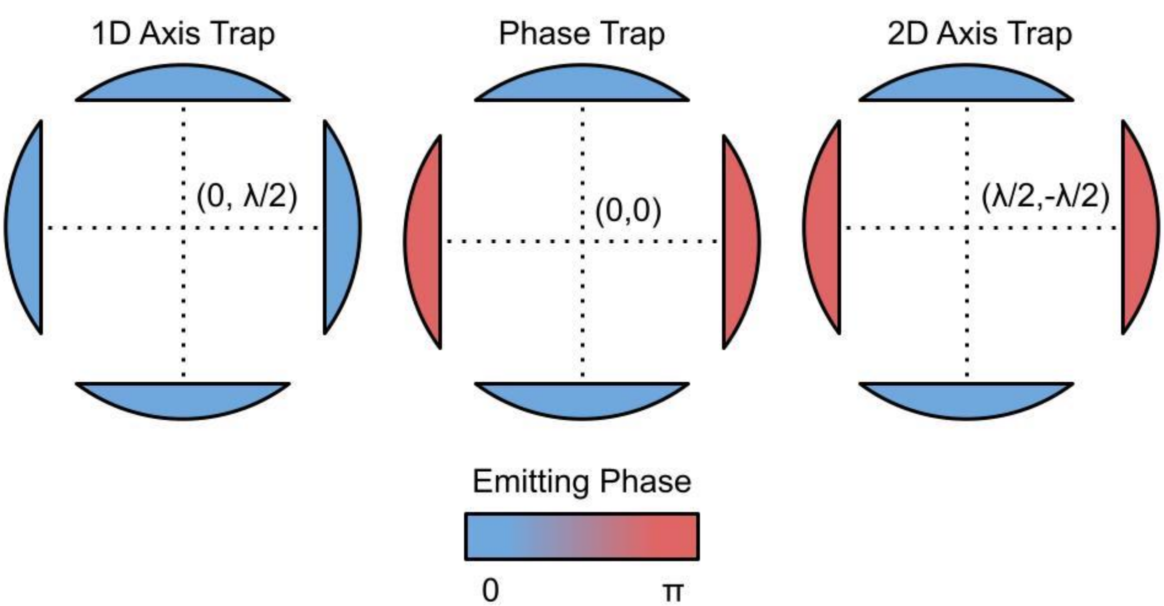

Figure 5: Emitting phase of arrays and location of trap with respect to common origin.

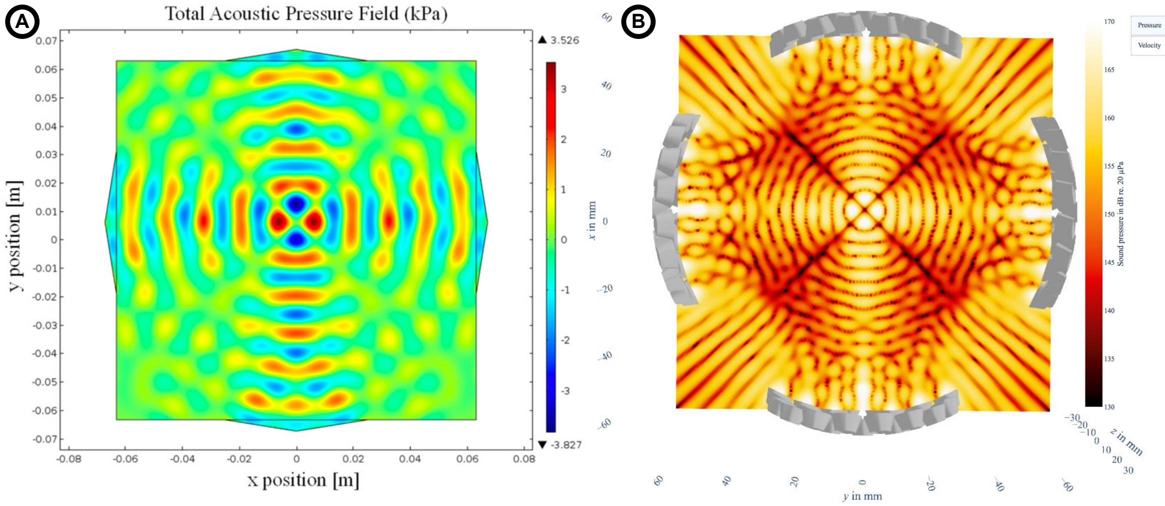

Figure 6: Models Comparison of 1D axis trap (A) is adapted from [5] (B) is generated from the Levitate toolbox.

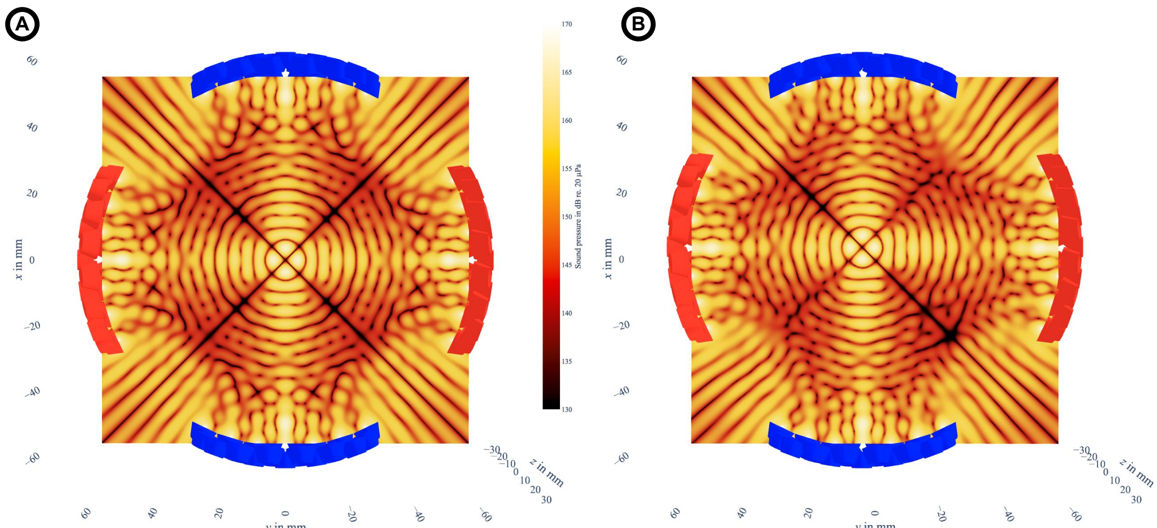

Figure 7: Pressure fields of (A) Phase Trap and (B) 2D Axis Trap generated from the Levitate toolbox.

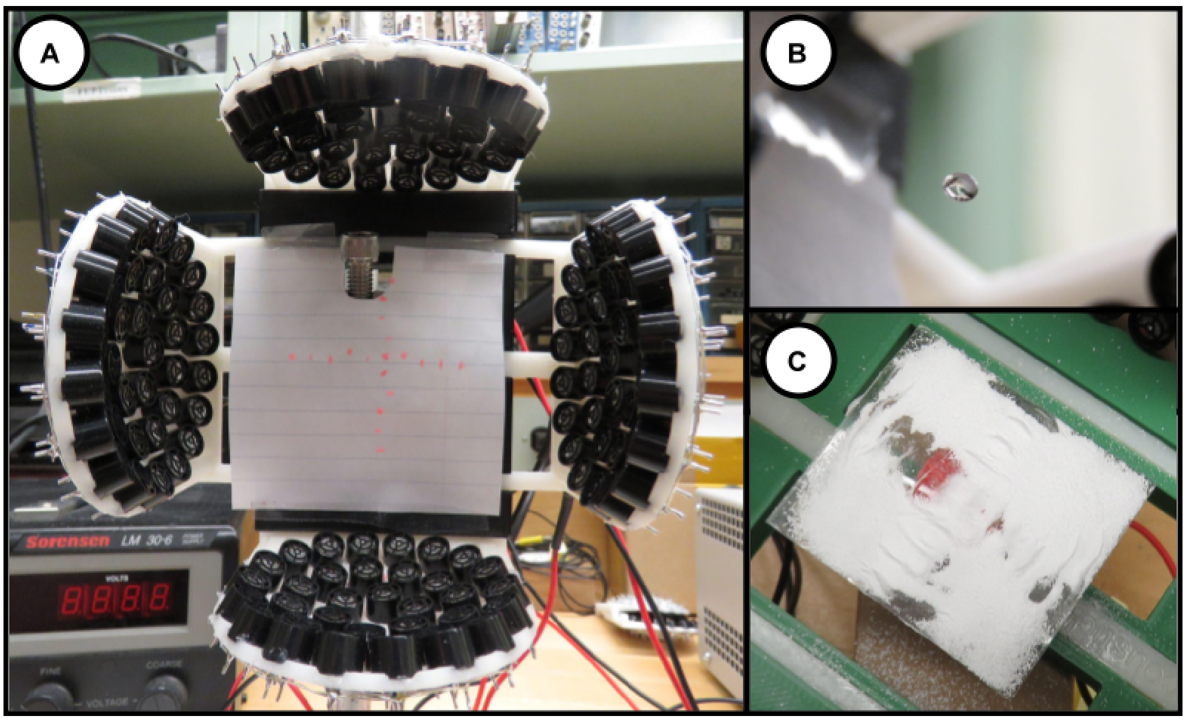

Figure 8: Various samples levitated by the two-axis acoustic levitator: (A) pieces of EPE packing foam and (B) a water drop. (C) A plane of fine white particles was used to locate nodes and anitnodes when aligning the arrays for the 1D Axis trap. When the axes are not spaced correctly, where they intersect becomes a chaotic high pressure region.